



**Extreme Precipitation and Emergency Room Visits for
Gastrointestinal Illness in Areas with and without
Combined Sewer Systems: An Analysis of
Massachusetts Data, 2003–2007**

**Jyotsna S. Jagai, Quanlin Li, Shiliang Wang, Kyle P. Messier,
Timothy J. Wade, and Elizabeth D. Hilborn**

<http://dx.doi.org/10.1289/ehp.1408971>

Received: 17 July 2014

Accepted: 6 April 2015

Advance Publication: 9 April 2015

This article will be available in its final, 508-conformant form 2–4 months after Advance Publication. If you need assistance accessing this article before then, please contact ehp508@niehs.nih.gov. Our staff will work with you to assess and meet your accessibility needs within 3 working days.



National Institute of
Environmental Health Sciences

Extreme Precipitation and Emergency Room Visits for Gastrointestinal Illness in Areas with and without Combined Sewer Systems: An Analysis of Massachusetts Data, 2003–2007

Jyotsna S. Jagai,^{1,2} Quanlin Li,³ Shiliang Wang,² Kyle P. Messier,⁴ Timothy J. Wade,² and Elizabeth D. Hilborn²

¹Division of Environmental and Occupational Health Sciences, School of Public Health, University of Illinois, Chicago, Illinois, USA; ²National Health and Environmental Effects Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Research Triangle Park, North Carolina, USA; ³Biostatistics and Bioinformatics Research Center, Samuel Oschin Comprehensive Cancer Institute, Cedars Sinai Medical Center, Los Angeles, California, USA; ⁴Department of Environmental Science and Engineering, Gillings School of Global Public Health, University of North Carolina, Chapel Hill, North Carolina, USA

Address correspondence to Jyotsna S. Jagai, Division of Environmental and Occupational Health Sciences, School of Public Health, University of Illinois, Chicago, 2121 W. Taylor St. M/C 922, Chicago, IL, 60612 USA. Telephone: 312-413-9735. E-mail: jjagai2@uic.edu

Running title: Precipitation and GI illness in areas with CSOs

Acknowledgments: The authors would like to thank Lisa Baxter for review of this manuscript.

Disclaimer: The views expressed in this manuscript are those of the individual authors and do not necessarily reflect the views and policies of the U.S. Environmental Protection Agency or the Massachusetts Division of Health Care Finance and Policy. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Competing financial interests: The authors declare that they have no competing interests.

Abstract

Background: Combined sewer overflows (CSOs) occur in combined sewer systems when sewage and stormwater runoff are released into water bodies potentially contaminating water sources. CSOs are often caused by heavy precipitation and are expected to increase with increasing extreme precipitation associated with climate change.

Objectives: To assess whether the association between heavy rainfall and rate of emergency room (ER) visits for gastrointestinal (GI) illness differed by the presence of CSOs.

Methods: For the study period 2003 – 2007, time-series of daily rate of ER visits for GI illness and meteorological data were organized for three exposure regions: 1) CSOs impacting drinking water sources; 2) CSOs impacting recreational waters; 3) no CSOs. A distributed lag Poisson regression assessed cumulative effects for an 8-day lag period following heavy (≥ 90 th and ≥ 95 th percentile) and extreme (≥ 99 th percentile) precipitation events, controlling for temperature and long term time trends.

Results: The association between extreme rainfall and rate of ER visits for GI illness differed among regions. Only the region with drinking waters exposed to CSOs demonstrated a significant increased cumulative risk for rate of ER visits for GI for all ages in the 8-day period following extreme rainfall, CRR: 1.13 (95% CI: 1.00, 1.28) compared to no rainfall.

Conclusions: Rate of ER visits for GI illness was associated with extreme precipitation in the area with CSO discharges to a drinking water source. Our findings suggest an increased risk for gastrointestinal illness among consumers whose drinking water source may be impacted by CSOs after extreme precipitation.

Introduction

Climate change is expected to bring changes in the frequency and severity of weather events, such as precipitation, flooding, and hurricanes, which can impact human health (Easterling et al. 2000; Ebi et al. 2006; Patz et al. 2001; Patz et al. 2005; Rose et al. 2001). Waterborne disease outbreaks are preceded by heavy precipitation events in the United States (U.S.) (Curriero et al. 2001) and the United Kingdom (Nichols et al. 2009) and extreme precipitation was linked to waterborne infections in Taiwan (Chen et al. 2012). Typical seasonal variations in rainfall and temperature have been associated with specific gastrointestinal diseases including cholera (Checkley et al. 2000; Olago et al. 2007; Pascual et al. 2000), cryptosporidiosis (Jagai et al. 2009), and rotavirus (Cook et al. 1990; Jagai et al. 2012; Levy et al. 2009). Acute gastrointestinal illness in children has been associated with rainfall four days prior (Drayna et al. 2010) and heavy rainfall was associated with increased risk of hospitalization for gastrointestinal illness (Bush et al. 2014).

Areas with combined sewer systems and aging infrastructure are particularly vulnerable to adverse water quality impacts resulting from increased precipitation events (Levin et al. 2002; Patz et al. 2008). Modern systems have separate collection for storm water and sewage, but many urban areas in the U.S. have combined sewer systems which collect rainwater runoff, domestic sewage, and industrial waste together, in one pipe, for transport to wastewater treatment facilities. During periods of heavy rainfall the volume of wastewater can exceed system capacity and is discharged directly to nearby streams, rivers, or other water bodies before treatment, resulting in a combined sewer overflow (CSO). CSO events can contaminate water sources with pathogenic microorganisms associated with untreated sewage, including protozoa, viruses, and bacteria such as *Cryptosporidium sp.*, *Salmonella sp.* and norovirus (Donovan et al.

2008; Gerba 2000; Levin et al. 2002; Marsalek and Rochfort 2004). The largest waterborne disease outbreak in the United States, which occurred in Milwaukee, WI in 1993, is thought to have been due to passage of cryptosporidium oocysts through the filtration system of a water treatment plant, following heavy rainfall that impaired source water quality (MacKenzie et al. 1995).

The U.S. Environmental Protection Agency (U.S. EPA) states that 772 communities of about 40 million people total, primarily in the Northeast, Great Lakes, and the Pacific Northwest, are served by combined sewer systems (U.S. EPA 2008). A control policy was established in 1994 to establish a protocol for reporting discharges through the National Pollutant Discharge Elimination System (U.S. EPA 1994). In addition, communities are expected to develop long-term CSO control plans to attain water quality standards compliant with the Clean Water Act (U.S. EPA 1995).

Studies have demonstrated that pathogen concentrations in receiving waters are higher following CSO events. A bacterial indicator of fecal contamination, *Escherichia coli*, was increased in recreational waters in Ontario, Canada (Marsalek and Rochfort 2004) and Lake Michigan (McLellan and Salmore 2003) following CSO events. Increases in concentrations of bacteria associated with sewage including *Streptococcus*, *Enterococcus* and several pathogenic viruses, were seen following CSO events in the Lower Passaic River (Donovan et al. 2008). Given the potential for increased CSO events due to changes in precipitation patterns associated with climate change it is important to better understand impacts on human health.

The goal of this study was to assess whether the association between heavy rainfall and rate of emergency room (ER) visits for gastrointestinal (GI) illness differed by the presence or absence

of CSO systems. The study used data from the state of Massachusetts, U.S., which has 24 permitted combined sewer systems located primarily in the central and eastern part of the state (Massachusetts Executive Office of Energy and Environmental Affairs 2014). We hypothesized that heavy precipitation ($\geq 90^{\text{th}}$, and 95^{th} percentile) and, especially, extreme precipitation ($\geq 99^{\text{th}}$ percentile) would be associated with an increased rate of ER visits for GI illness in areas with CSOs compared to areas without CSOs.

Methods

Exposure classification

Locations of CSO outfalls in Massachusetts were obtained from U.S. EPA Enforcement & Compliance History Online System (U.S. EPA 2014b). We considered three regions for analysis; one with recreational water exposure to CSOs (Exposed - Recreational Water Region), one with drinking water exposure to CSOs (Exposed - Drinking Water Region), and an area without exposure to CSOs (Unexposed Region) (Figure 1). In the Exposed - Recreational Water Region CSOs discharge directly into a water body used for recreation, the Boston Harbor. This region included 24 neighboring cities and towns surrounding the harbor likely to recreate in the harbor. Boston Harbor is typically used for sailing, fishing, kayaking, and recreational activities with limited direct water contact. In the Exposed - Drinking Water Region, which included 11 neighboring towns, CSOs discharge into river waters used as a drinking water source. Despite being a historically industrial and polluted waterway, the Merrimack River, which serves this region, is the only river in New England from which communities draw drinking water directly (Leo 2014). The Unexposed Region included 9 neighboring towns which do not have CSO outfalls.

Exposure data

Daily rainfall and temperature data were obtained from the National Climatic Data Center (<http://www.ncdc.noaa.gov/>). One weather station in each exposure region was selected based on completeness of data for the study period 2003-2007. Three time series for each region indicating days with precipitation $\geq 90^{\text{th}}$, 95^{th} , and 99^{th} percentile were developed based on the overall distribution for the region, allowing for sensitivity analysis. The 99^{th} percentile was included because we anticipated these events would be severe enough to potentially trigger a CSO event.

Time series of daily average temperature for each exposure region from the same weather stations was included in the models as a potential confounder. Temperature has been associated with environmental transmission of pathogens (Checkley et al. 2000; Fleury et al. 2006; Naumova et al. 2007) and the health of vulnerable subpopulations (Kovats and Hajat 2008).

Emergency room data

Daily emergency room (ER) visits were obtained from the State of Massachusetts Division of Health Care Finance and Policy (<http://chiamass.gov/>) for 2003-2007. Each record represents an ER visit and includes patient information, such as age, sex, town of residence, diagnoses, and admission data and time.

Data for ER visits that included diagnosis for gastrointestinal illness were abstracted from the complete dataset. GI illness was defined by the following ICD-9CM codes: 001-009, 558.9, 787.0, 787.01, 787.03, 787.4, 787.9, 787.91. Cases were grouped based on town of residence to create a daily time series of ER visits for each exposure region. Due to the potential for differences in susceptibility according to age, analyses were also stratified by age group (< 5, 5 –

≤ 19 , $20 - \leq 64$, and ≥ 65 years.) Daily rates of ER visits for GI illness per 100,000 population were calculated using population estimates for 2005 (U.S. Census 2011), the mid-point of the study period, for each region and by age group. The use of limited, de-identified admissions records was designated as non-human subjects research and exempt from Institutional Review Board review as determined by the Human Subjects Research Protocol Officer of the U.S. EPA, Office of Research and Development, Research Triangle Park, North Carolina.

Data to describe the towns in each exposure region were abstracted from the 2000 US Census of Population and Housing (U.S. Census 2013), including population density (population per square mile), median per capita income (dollars), household size (average number of people per household), septic tank density (number of septic tanks per square mile). ANOVA was used to assess differences in these descriptive factors across exposure regions. An $\alpha = 0.05$ was considered statistically significant.

Statistical analysis

Model Estimation. We used a distributed lag Poission regression model (Schwartz 2000; Zanobetti et al. 2000) to assess associations between heavy precipitation and daily rates of ER visits for GI infections in the three regions. The distributed lag model estimates cumulative effect of precipitation over the entire lag period following a heavy precipitation event (Gasparrini et al. 2010; Gasparrini 2011). This allows for consideration of various pathogens that cause GI illness but have different incubation periods and has been previously used in studies of turbidity and GI infections (Morris et al. 1998; Naumova et al. 2003). We used a quasi-Poission distribution (Tjur 1998) to account for overdispersion. The model is given by Equation 1 where *ER* represents the time series of rate of ER visits for GI illness on day *t*, *precip* is the time series indicating days with precipitation greater than the cut-off percentile (90th, 95th, or 99th), *temp* is

the time series for daily average temperature, and $ns(t, f)$ represents the natural spline function for time used to control for unmeasured covariates. The summation is calculated over the selected number of lag days, lag , following the heavy precipitation events. β_l is the lag weight or coefficient placed on l days previous to the date of heavy precipitation. We used the finite distribution lag model assuming a maximum number of lag days beyond which heavy precipitation does not affect the rate of ER visits for GI illness. The degrees of freedom of f in the natural spline function was determined based on the minimum residual autocorrelation (Peng et al. 2006).

$$\log[E(ER_t)] = \alpha + \sum_{l=0}^{lag} \beta_l * precip_{t-l} + \gamma * temp_t + ns(t, f) \quad [1]$$

For interpretation, the CRR is the cumulative risk of the rate of ER visits for GI for the 8-day period following a day with rainfall over the 99th percentile compared to an 8-day period following days without rainfall. Analyses were conducted in R (R Foundation for Statistical Computing, Vienna, Austria) and specifically the DLNM package for the distributed lag model (Gasparrini 2011).

Lag Selection. Previous studies demonstrated that GI illness tends to peak several days after an extreme precipitation event (Schuster et al. 2005; Schwartz et al. 1997; Schwartz et al. 2000).

The incubation period for gastrointestinal pathogens varies from an average of a few hours, for bacterial pathogens, up to 7 days, for protozoal pathogens (Nelson and Williams 2013). We assessed an 8-day lag to capture the majority of GI illnesses caused by waterborne exposure. We also considered 4-day and 15-day lag periods to evaluate lag times for different pathogens. We utilized a uniform weighted lag structure, assuming that probability of infection would be equal across the lag period.

Seasonal sub-analysis. A sub-analysis to assess associations between extreme precipitation ($\geq 99^{\text{th}}$ percentile) and rate of ER visits for GI illness by season was conducted for each region and age category. Seasons were defined, as in previous studies (Curriero et al. 2001; Nichols et al. 2009), as Spring (March, April, May), Summer (June, July, August), Fall (September, October, November), Winter (December, January, February).

Results

Descriptive analysis

The three regions experienced similar rainfall patterns over the 5-year (1826 days) study period. The Exposed – Drinking Water Region had 999 days of rain (55% of days), ranging from 0.005 to 6.76 inches. The 90th, 95th and 99th percentiles for rainfall were 0.41, 0.64, and 1.33 inches, respectively. The Exposed – Recreational Water Region had 848 days of rainfall (46% of days), ranging from 0.005 to 4.32 inches. The 90th, 95th and 99th percentiles for rainfall for were 0.37, 0.70, and 1.60 inches, respectively. The Unexposed Region had 928 days of rainfall (51% of days), ranging from 0.005 to 3.61 inches. The 90th, 95th and 99th percentiles for rainfall were 0.39, 0.77, and 1.97 inches, respectively. Time-series for daily rate of ER visits by region with indication of days of extreme precipitation ($\geq 99^{\text{th}}$ percentile) are shown in Figure 2.

The three regions varied by size and characteristics. As expected, the most urban of the three regions, the Exposed – Recreational Water region that includes the Boston metropolitan area, had the highest population, population density, and median per capita income and the lowest average household size and septic tank density (Table 1).

Model results

The distributed lag models demonstrated that the association between rainfall events and rate of ER visits for GI illness differed by the presence and type of CSOs only when the 99th percentile was used as the cut-off. The 90th and 95th percentile cut-offs for precipitation did not demonstrate significant positive associations with rate of ER visits for GI illness in any region (Table 2). In the Exposed – Drinking Water Region there was a significantly increased cumulative risk for rate of ER visits for GI illness for all ages 8 days following a 99th percentile rainfall event, CRR: 1.13 (95% CI: 1.00, 1.28), after controlling for daily average temperature and a time trends (Table 2). This suggests a 13% increase in the expected rate of ER visits over the 8 day period following an extreme precipitation event compared to no precipitation in the region with CSO outfalls to receiving waters that are a source of drinking water. In the Exposed – Recreational Water Region and the Unexposed Region there was no association between rate of ER visits for GI and extreme precipitation events, CRR: 0.95 (95% CI: 0.88, 1.03) and CRR: 1.05 (95% CI: 0.84, 1.32), respectively.

Positive associations were observed for all age categories in the Exposed – Drinking Water Region. The largest estimated increase, though not statistically significant, was among residents over 65 years of age, CRR: 1.32 (95% CI: 0.92, 1.88). Strong associations were also seen in children (5 – ≤19 years), CRR: 1.23 (95% CI: 0.89, 1.69). The Exposed – Recreational Water Region did not demonstrate positive associations for any age category. The Unexposed Region demonstrated positive associations in the adult (20 – ≤64 years) and elderly (≥ 65 years) age categories, CRR: 1.20 (95% CI: 0.91, 1.59) and CRR: 1.31 (95% CI: 0.71, 2.42), respectively.

The results and trends for rainfall ≥ 99th percentile and GI illness using 4-day and 15-day lag periods were similar to model estimates for the 8-day lag (Supplemental Material, Table S1). The

consistent positive associations estimated for the Exposed– Drinking Water Region suggest an increase in ER visits during the first 4 days that may continue for up to 15 days after extreme rainfall events.

Discussion

We found evidence of an association between the rate of ER visits for GI illness and heavy precipitation that appeared to be limited to the region with CSO outfalls to drinking water sources. Specifically, we estimated that compared with no precipitation, extreme precipitation events ($\geq 99^{\text{th}}$ percentile) were associated with a 13% increase in the expected rate of ER visits for GI illness in this region over an 8-day period for all age groups combined. In the region with CSO outfalls to recreational waters and the region without exposure to CSO outfalls there were no associations between extreme rainfall events and rate of ER visits for GI illness. Our findings suggest that extreme precipitation events may trigger CSO events that affect local drinking water quality in some areas. Our study is the first that we know of to demonstrate an association between extreme precipitation and GI illness that differs according to the presence of CSOs and whether the receiving waters are used for recreation or as a source of drinking water.

Contrary to previous findings, heavy rainfall events ($\geq 90^{\text{th}}$ and 95^{th} percentile) were not associated with increased rates of ER visits for GI illness in any of the three exposure regions (Bush et al. 2014; Carlton et al. 2014; Drayna et al. 2010; Nichols et al. 2009; Curriero et al. 2001). Drinking water turbidity, often a result of heavy precipitation, was positively associated with hospital admissions for children between 0 and 15 years of age in Philadelphia at 8 and 13-day lags (Schwartz et al. 1997). An increase in interquartile range of turbidity was associated with a 1.47 increase in relative risk of self-reported gastrointestinal infections in the town of Cherepovets, Russia (Egorov et al. 2003). On the other hand, a study of 8 drinking water

treatment plants in Atlanta demonstrated no association between filtered water turbidity and emergency department visits for GI illness (Tinker et al. 2008). Rainfall events greater than the 93rd percentile were associated with a 2.28 times (95% CI: 1.22, 4.23) increased risk for waterborne outbreaks in Canada (Thomas et al. 2006). A study conducted in the UK estimated that laboratory-confirmed cryptosporidiosis increased by 27%, 95%CI (21%, 33%) when the cumulative rainfall for the prior week exceeded the 75th percentile, or 0.86 inches (Naumova et al. 2005). A study of pediatric emergency room visits for acute gastrointestinal illness found that any rainfall 4 days prior was significantly associated with an 11% increase in emergency room visits for GI illness (Drayna et al. 2010). A recent study conducted in Chennai, India estimated an increased cumulative risk ratio for hospital admissions for GI illness for the 15-day period following an extreme precipitation event (≥ 90 th percentile) was 1.60 (95% CI: 1.29, 1.98) (Bush et al. 2014). Previous work on the effect of precipitation on GI illness has also demonstrated stronger associations in the most vulnerable age sub-populations, children and the elderly (Bush et al. 2014; Drayna et al. 2010; Redman et al. 2007). Our age stratified results demonstrated associations in children under five, children between 5 and 19 years, and the elderly (≥ 65 years) stronger than the association in the adult (20-64 years) category in the Exposed-Drinking Water Region.

Few studies have considered the impact of CSO events on human enteric infection. Using a risk assessment approach, one study estimated the risk of contracting GI illness from incidental ingestion of water affected by CSO outfalls ranged from 0.14 to nearly 0.70 over the course of a year for visitors and recreators, respectively (Donovan et al. 2008). Our findings in the Exposed – Drinking Water Region are consistent with the findings of Redman et al. who found that pediatric emergency room visits for diarrheal illness increased 3-7 days following sewage bypass

events for those using drinking water from Lake Michigan (Redman et al. 2007). Another study in Wisconsin also demonstrated associations between a winter sewage release event and increased pediatric visits for GI illness (Drayna et al. 2010). Although CSOs are known to adversely impact source water quality and introduce pathogens (Donovan et al. 2008; Marsalek and Rochfort 2004; McLellan and Salmore 2003), we did not confirm that municipal water supplies in the Exposed – Drinking Water Region were adversely impacted during the study period.

Selection of an appropriate lag period and structure for the studies of waterborne pathogens must consider expected time due to pathogen transport in the environment, pathogen incubation periods, and time to seek care after illness begins (Egorov et al. 2003). In addition, environmental pathogen transport can vary significantly based on the route of exposure, either drinking or recreational water. In previous studies of associations between drinking water turbidity and GI illness, authors concluded that a Poisson or gamma distribution and lag structures with a mean of 7-8 days were appropriate for estimation of distributed effects (Egorov et al. 2003; Naumova and Macneill 2008). The lag periods considered in our study, 4, 8, and 15 days, are comparable to previous studies (Bush et al. 2014; Drayna et al. 2010; Egorov et al. 2003; Schwartz et al. 1997). However we assumed a uniform weighted lag structure and the use of a Poisson or gamma distribution lag structure may provide more accurate estimation of cumulative risk.

We did not observe an association between heavy precipitation and rate of ER visits for GI in areas with recreational water impacted by CSOs. This lack of an association may be because recreational water contact is likely to be highly localized and seasonal. Though a recent study of triathletes found a significantly increased risk for swimming in contaminated waters (Harder-

Lauridsen et al. 2013), the majority of recreational activities in our study area, Boston Harbor, would involve only limited water contact and therefore the amount of water ingested may not be sufficient to cause an observable increase in rate ER visits for GI illness (Dorevitch et al. 2011; Dorevitch et al. 2012). Though, previous studies have demonstrated effect modification by season (Bush et al. 2014; Carlton et al. 2014; Drayna et al. 2010; Nichols et al. 2009), our seasonality analysis did not demonstrate associations between extreme rainfall and rate of ER visits for GI illness in any of the three regions suggesting that increased seasonal recreational exposure is not associated with increases in rates of ER visits for GI illness (Supplemental Material, Table S2). Also, contrary to previous findings, there was no association between extreme precipitation in regions without a CSO, potentially due to the lower concentrations of untreated sewage discharged to water bodies.

The three exposure regions considered were heterogeneous and differed significantly from each other, which is a study limitation. Previous studies reported that the confounders and risk factors for enteric infections in Massachusetts were geographically distributed. The use of mixed surface and ground drinking water supplies (Naumova et al. 2000) and high septic tank density (Cohen et al. 2008), both of which are geographically distributed, have been associated with elevated risk for enteric infections in Massachusetts. Differences in these factors among our exposure regions may explain some of the differences in associations between extreme precipitation and rates of ER visits for GI illness among the three regions. However, due to the nature of CSOs, which are typically built in older, urban areas, we are unable to define more comparable exposure regions to explore this association.

With climate change, it is predicted that extreme rainfall events will increase and therefore increase the likelihood of CSO events (Patz et al. 2008). In the U.S., it has been observed that

since 1990 a large percentage of precipitation has come in the form of intense single day events (U.S. EPA 2014a). In the Northeast, single day heavy rainfall events are expected to increase and the 99th percentile of rainfall events has increased by over an inch for most of the region (Spierre and Wake 2010). The increase in intensity of precipitation events will trigger more CSO events as these systems are not designed to handle large volumes of water. Increases in overflow events will put more water systems, both drinking and recreational, at an increased risk for pathogen contamination. CSO systems are common in densely populated urban areas in the U.S., such as New England and the Great Lakes; therefore, these events can put large populations at risk for increased gastrointestinal illness. Though, communities are expected to develop long-term CSO control plans (U.S. EPA 1995), these plan can be expensive and require significant infrastructure changes therefore it is useful to understand the health impact of these events.

Although we observed an association between extreme precipitation and rate of ER visits for GI illness in the Exposed – Drinking Water Region, we lacked detailed data to confirm the drinking water sources were impacted by the severe precipitation events and mediated by a CSO. This analysis would, ideally, be conducted using dates of CSO events however, these data were not available for this analysis. The emergency room data are collected for administrative purposes and do not provide individual level information on behaviors, such as drinking water source and recreational water exposures, which could be used to adjust for in this analysis. Studies have demonstrated that GI illness is underreported and only a portion of actual cases are recognized (Craun et al. 2010; Schuster et al. 2005; Yoder et al. 2008). In addition, emergency room visits for gastrointestinal illness only represent a fraction of all gastrointestinal illnesses in a

community, and may not be representative of GI illness occurring in the community (Mead et al. 1999).

Conclusions

We demonstrated that the association between extreme rainfall and emergency room visits for gastrointestinal diseases differed by the presence and type of CSOs. Only in the region with CSO outfalls to drinking water sources did we find a significant increase in the expected rate of ER visits for GI illness for all ages in the 8-day period following an extreme precipitation event after controlling for daily average temperature and a time trends. In light of expected increases in extreme precipitation events, our findings suggest that drinking water quality may be adversely impacted by the presence of CSOs that discharge into drinking water sources after heavy rainfall.

References

- Bush KF, O'Neill MS, Li S, Mukherjee B, Hu H, Ghosh S, et al. 2014. Associations between extreme precipitation and gastrointestinal-related hospital admissions in Chennai, India. *Environ Health Perspect* 122:249-254.
- Carlton EJ, Eisenberg JN, Goldstick J, Cevallos W, Trostle J, Levy K. 2014. Heavy rainfall events and diarrhea incidence: The role of social and environmental factors. *Am J Epidemiol* 179:344-352.
- Checkley W, Epstein LD, Gilman RH, Figueroa D, Cama RI, Patz JA, et al. 2000. Effect of El Niño and ambient temperature on hospital admissions for diarrhoeal diseases in Peruvian children. *Lancet* 355:442-450.
- Chen MJ, Lin CY, Wu YT, Wu PC, Lung SC, Su HJ. 2012. Effects of extreme precipitation to the distribution of infectious diseases in Taiwan, 1994-2008. *PloS One* 7:e34651.
- Cohen SA, Egorov AI, Jagai JS, Matyas BT, DeMaria A, Jr., Chui KK, et al. 2008. The seeds of two gastrointestinal diseases: Socioeconomic, environmental, and demographic factors related to cryptosporidiosis and giardiasis in Massachusetts. *Environ Res* 108:185-191.
- Cook SM, Glass RI, LeBaron CW, Ho MS. 1990. Global seasonality of rotavirus infections. *Bull World Health Organ* 68:171-177.
- Craun GF, Brunkard JM, Yoder JS, Roberts VA, Carpenter J, Wade T, et al. 2010. Causes of outbreaks associated with drinking water in the United States from 1971 to 2006. *Clin Microbiol Rev* 23:507-528.
- Curriero FC, Patz JA, Rose JB, Lele S. 2001. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *Am J Public Health* 91:1194-1199.
- Donovan E, Unice K, Roberts JD, Harris M, Finley B. 2008. Risk of gastrointestinal disease associated with exposure to pathogens in the water of the Lower Passaic River. *Appl Environ Microbiol* 74:994-1003.
- Dorevitch S, Panthi S, Huang Y, Li H, Michalek AM, Pratap P, et al. 2011. Water ingestion during water recreation. *Water Res* 45:2020-2028.
- Dorevitch S, Pratap P, Wroblewski M, Hryhorczuk DO, Li H, Liu LC, et al. 2012. Health risks of limited-contact water recreation. *Environ Health Perspect* 120:192-197.

- Drayna P, McLellan SL, Simpson P, Li SH, Gorelick MH. 2010. Association between rainfall and pediatric emergency department visits for acute gastrointestinal illness. *Environ Health Perspect* 118:1439-1443.
- Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO. 2000. Climate extremes: Observations, modeling, and impacts. *Science* 289:2068-2074.
- Ebi KL, Mills DM, Smith JB, Grambsch A. 2006. Climate change and human health impacts in the United States: An update on the results of the U.S. National assessment. *Environ Health Perspect* 114:1318-1324.
- Egorov AI, Naumova EN, Tereschenko AA, Kislitsin VA, Ford TE. 2003. Daily variations in effluent water turbidity and diarrhoeal illness in a Russian city. *Int J Environ Heal R* 13:81-94.
- Fleury M, Charron DF, Holt JD, Allen OB, Maarouf AR. 2006. A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in two Canadian provinces. *Int J Biometeorol* 50:385-391.
- Gasparrini A, Armstrong B, Kenward MG. 2010. Distributed lag non-linear models. *Stat Med* 29:2224-2234.
- Gasparrini A. 2011. Distributed lag linear and non-linear models in r: The package dlnm. *J State Softw* 43:1-20.
- Gerba CP. 2000. Domestic waste and waste treatment. In: *Environmental microbiology*, (Maier RM, Pepper IL, Gerba CP, eds). San Diego, CA: Academic Press, 491-503.
- Harder-Lauridsen NM, Kuhn KG, Erichsen AC, Molbak K, Ethelberg S. 2013. Gastrointestinal illness among triathletes swimming in non-polluted versus polluted seawater affected by heavy rainfall, Denmark, 2010-2011. *PloS One* 8:e78371.
- Jagai JS, Castronovo DA, Monchak J, Naumova EN. 2009. Seasonality of cryptosporidiosis: A meta-analysis approach. *Environ Res* 109:465-478.
- Jagai JS, Sarkar R, Castronovo D, Kattula D, McEntee J, Ward H, et al. 2012. Seasonality of rotavirus in south Asia: A meta-analysis approach assessing associations with temperature, precipitation, and vegetation index. *PloS One* 7:e38168.
- Kovats RS, Hajat S. 2008. Heat stress and public health: A critical review. *Annu Rev Public Health* 29:41-55.
- Leo A. 2014. State boosts key water projects: Funding targeted to improve quality. *Boston Globe* (Boston) April 20, 2014.

Levin RB, Epstein PR, Ford TE, Harrington W, Olson E, Reichard EG. 2002. U.S. Drinking water challenges in the twenty-first century. *Environ Health Perspect* 110 Suppl 1:43-52.

Levy K, Hubbard AE, Eisenberg JN. 2009. Seasonality of rotavirus disease in the tropics: A systematic review and meta-analysis. *Int J Epidemiol* 38:1487-1496.

MacKenzie WR, Schell WL, Blair KA, Addiss DG, Peterson DE, Hoxie NJ, et al. 1995. Massive outbreak of waterborne cryptosporidium infection in Milwaukee, Wisconsin: Recurrence of illness and risk of secondary transmission. *Clin Infect Dis* 21:57-62.

Marsalek J, Rochfort Q. 2004. Urban wet-weather flows: Sources of fecal contamination impacting on recreational waters and threatening drinking-water sources. *J Toxicol Env Health* 67:1765-1777.

Massachusetts Executive Office of Energy and Environmental Affairs. 2014. Sanitary sewer systems & combined sewer overflows. Available: <http://www.mass.gov/eea/agencies/massdep/water/wastewater/sanitary-sewer-systems-and-combined-sewer-overflows.html> [accessed 25 March 2015].

McLellan SL, Salmore AK. 2003. Evidence for localized bacterial loading as the cause of chronic beach closings in a freshwater marina. *Water Res* 37:2700-2708.

Mead PS, Slutsker L, Dietz V, McCaig LF, Bresee JS, Shapiro C, et al. 1999. Food-related illness and death in the United States. *Emerg Infect Dis* 5:607-625.

Morris RD, Naumova EN, Griffiths JK. 1998. Did Milwaukee experience waterborne cryptosporidiosis before the large documented outbreak in 1993? *Epidemiology* 9:264-270.

Naumova EN, Chen JT, Griffiths JK, Matyas BT, Estes-Smargiassi SA, Morris RD. 2000. Use of passive surveillance data to study temporal and spatial variation in the incidence of giardiasis and cryptosporidiosis. *Public Health Rep* 115:436-447.

Naumova EN, Egorov AI, Morris RD, Griffiths JK. 2003. The elderly and waterborne cryptosporidium infection: Gastroenteritis hospitalizations before and during the 1993 Milwaukee outbreak. *Emerg Infect Dis* 9:418-425.

Naumova EN, Christodouleas J, Hunter PR, Syed Q. 2005. Effect of precipitation on seasonal variability in cryptosporidiosis recorded by the North West England surveillance system in 1990-1999. *J Water Health* 3:185-196.

Naumova EN, Jagai JS, Matyas B, DeMaria A, Jr., MacNeill IB, Griffiths JK. 2007. Seasonality in six enterically transmitted diseases and ambient temperature. *Epidemiol Infect* 135:281-292.

Naumova EN, MacNeill IB. 2008. Time-distributed effect of exposure and infectious outbreaks. *Environmetrics* 20:235-248.

- Nelson KE, Williams C. 2013. *Infectious Disease Epidemiology: Theory and Practice*: Jones & Bartlett Learning.
- Nichols G, Lane C, Asgari N, Verlander NQ, Charlett A. 2009. Rainfall and outbreaks of drinking water related disease and in England and Wales. *J Water Health* 7:1-8.
- Olago D, Marshall M, Wandiga SO, Opondo M, Yanda PZ, Kanalawe R, et al. 2007. Climatic, socio-economic, and health factors affecting human vulnerability to cholera in the Lake Victoria Basin, East Africa. *Ambio* 36:350-358.
- Pascual M, Rodo X, Ellner SP, Colwell R, Bouma MJ. 2000. Cholera dynamics and El Niño-Southern Oscillation. *Science* (New York, NY 289:1766-1769).
- Patz JA, McGeehin MA, Bernard SM, Ebi KL, Epstein PR, Grambsch A, et al. 2001. The potential health impacts of climate variability and change for the United States. Executive summary of the report of the health sector of the U.S. National assessment. *J Environ Health* 64:20-28.
- Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. 2005. Impact of regional climate change on human health. *Nature* 438:310-317.
- Patz JA, Vavrus SJ, Uejio CK, McLellan SL. 2008. Climate change and waterborne disease risk in the great lakes region of the U.S. *Am J Prev Med* 35:451-458.
- Peng RD, Dominici F, Louis TA. 2006. Model choice in time series studies of air pollution and mortality. *J R Stat Soc* 169:179–203.
- Redman RL, Nenn CA, Eastwood D, Gorelick MH. 2007. Pediatric emergency department visits for diarrheal illness increased after release of undertreated sewage. *Pediatrics* 120:e1472-1475.
- Rose JB, Epstein PR, Lipp EK, Sherman BH, Bernard SM, Patz JA. 2001. Climate variability and change in the United States: Potential impacts on water- and foodborne diseases caused by microbiologic agents. *Environ Health Perspect* 109 Suppl 2:211-221.
- Schuster CJ, Ellis AG, Robertson WJ, Charron DF, Aramini JJ, Marshall BJ, et al. 2005. Infectious disease outbreaks related to drinking water in Canada, 1974-2001. *C J Public Health* 96:254-258.
- Schwartz J, Levin R, Hodge K. 1997. Drinking water turbidity and pediatric hospital use for gastrointestinal illness in Philadelphia. *Epidemiology* 8:615-620.
- Schwartz J. 2000. The distributed lag between air pollution and daily deaths. *Epidemiology* 11:320-326.

- Schwartz J, Levin R, Goldstein R. 2000. Drinking water turbidity and gastrointestinal illness in the elderly of Philadelphia. *J Epidemiol Commun H* 54:45-51.
- Spierre SG, Wake C. 2010. Trends in extreme precipitation events for the Northeastern United States 1948-2007. Durham, NH: Carbon Solutions New England, University of New Hampshire.
- Thomas KM, Charron DF, Waltner-Toews D, Schuster C, Maarouf AR, Holt JD. 2006. A role of high impact weather events in waterborne disease outbreaks in Canada, 1975 - 2001. *Int J Environ Heal R* 16:167-180.
- Tinker SC, Moe CL, Klein M, Flanders WD, Uber J, Amirtharajah A, et al. 2008. Drinking water turbidity and emergency department visits for gastrointestinal illness in Atlanta, 1993-2004. *J Expo Sci Environ Epidemiol* 20:19-28.
- Tjur T. 1998. Nonlinear regression, quasi likelihood, and overdispersion in generalized linear models. *Am Stat* 52:222-227.
- U.S. Census (U.S. Census Bureau). 2011. Population estimates, vintage 2005: State tables. Available: https://www.census.gov/popest/data/historical/2000s/vintage_2005/index.html [accessed 25 March 2015].
- U.S. Census (U.S. Census Bureau). 2013. Census of population and housing. Available: <http://www.census.gov/prod/www/decennial.html> [accessed 25 March 2015].
- U.S. EPA (U.S. Environmental Protection Agency). 1994. Combined sewer overflow control policy. Available: <http://water.epa.gov/polwaste/npdes/cso/CSO-Control-Policy.cfm> [accessed 25 March 2015].
- U.S. EPA (U.S. Environmental Protection Agency). 1995. Combined sewer overflows - guidance for long-term control plan. Available: <http://water.epa.gov/polwaste/npdes/cso/upload/owm0272.pdf> [accessed 25 March 2015].
- U.S. EPA (Environmental Protection Agency). 2008. Combined sewer overflow home: overview. Available: <http://water.epa.gov/polwaste/npdes/cso/index.cfm> [accessed 25 March 2015].
- U.S. EPA (U.S. Environmental Protection Agency). 2014a. Climate change indicators In the United States: Heavy precipitation. Available: <http://www.epa.gov/climatechange/science/indicators/weather-climate/heavy-precip.html> [accessed 25 March 2015].
- U.S. EPA (U.S. Environmental Protection Agency). 2014b. ECHO - Enforcement and Compliance History Online. Available: <https://echo.epa.gov/> [accessed 25 March 2015].

Yoder J, Roberts V, Craun GF, Hill V, Hicks LA, Alexander NT, et al. 2008. Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking--United States, 2005-2006. *MMWR Surveill Summ* 57:39-62.

Zanobetti A, Wand MP, Schwartz J, Ryan LM. 2000. Generalized additive distributed lag models: Quantifying mortality displacement. *Biostatistics* (Oxford, England) 1:279-292.

Table 1. Descriptive statistics for each of the three exposure regions, including number of cities and towns, total population (2005), total population by age group (2005), total number of emergency room visits for gastrointestinal illness, number of daily emergency room visits for gastrointestinal illness, and daily rate of emergency room visits for gastrointestinal illness per 100,000 population and socio-demographic factors, including average household size, population density, septic tank density, and median per capita income.

Characteristic	Exposed - Drinking Water Region	Exposed – Recreational Water Region	Unexposed Region	p-value^a
Cities/Towns	11	24	9	
Total Population^b	478,071	1,501,163	156,264	
< 5 years	35,800	83,649	10,733	
5-19 years	108,670	267,468	30,684	
20-64 years	277,049	960,827	92,902	
≥ 65 years	56,552	189,218	21,945	
Average daily ER visits for GI illness	19.37 ± 2.93	56.01 ± 9.60	5.25 ± 0.29	
Average daily rate of ER visits for GI illness (per 100,000 population)	4.05 ± 0.62	3.73 ± 0.61	3.36 ± 0.16	
Population density (population/sq. mile)^c	2732.17 ± 3177.53	5983.30 ± 5133.24	552.64 ± 214.94	0.004
Median per capita income (dollars)^c	24,953 ± 8,951	27,113 ± 7,660	23,738 ± 5,787	0.27
Average household size (N)^c	2.72 ± 0.13	2.47 ± 0.22	2.84 ± 0.15	<0.0001
Septic tank density (tanks/sq. mile)^c	0.05 ± 0.04	0.02 ± 0.04	0.14 ± 0.03	<0.0001

^aDifferences across groups assessed using ANOVA. ^bPopulation estimates for 2005 from U.S. Census. (U.S. Census 2011). ^cSocio-demographic data from U.S. Census 2000. (U.S. Census 2013).

Table 2. Cumulative risk ratios of rate of emergency room visits for gastrointestinal illness associated with precipitation ($\geq 90^{\text{th}}$, 95^{th} , and 99^{th} percentile) by exposure region and age group for all three regions as estimated by distributed lag model with an 8-day lag.

Age Group	Number of ER Visits (N)	90 th Percentile Cumulative RR ^a (95% CI)	95 th Percentile Cumulative RR ^a (95% CI)	99 th Percentile Cumulative RR ^a (95% CI)
Exposed – Drinking Water Region				
All ages	35,358	0.97 (0.93, 1.01)	0.95 (0.89, 1.01)	1.13 (1.00, 1.28)
< 5 years	8,526	0.98 (0.91, 1.07)	0.95 (0.85, 1.07)	1.19 (0.95, 1.49)
5 – ≤ 19 years	6,267	1.02 (0.91, 1.14)	1.02 (0.88, 1.19)	1.23 (0.89, 1.69)
20 – ≤ 64 years	17,577	0.95 (0.89, 0.99)	0.94 (0.87, 1.01)	1.08 (0.91, 1.27)
≥ 65 years	2,988	0.97 (0.86, 1.11)	0.98 (0.82, 1.18)	1.32 (0.92, 1.88)
Exposed – Recreational Water Region				
All ages	102,272	0.99 (0.97, 1.02)	0.98 (0.95, 1.02)	0.95 (0.88, 1.03)
< 5 years	25,197	0.97 (0.92, 1.03)	0.98 (0.91, 1.05)	0.92 (0.78, 1.09)
5 – ≤ 19 years	15,613	0.92 (0.86, 0.98)	0.94 (0.85, 1.04)	0.93 (0.74, 1.15)
20 – ≤ 64 years	53,091	1.00 (0.97, 1.04)	0.98 (0.93, 1.02)	0.95 (0.86, 1.06)
≥ 65 years	8,371	1.06 (0.98, 1.14)	1.03 (0.93, 1.14)	0.94 (0.74, 1.20)
Unexposed Region				
All ages	9,584	1.02 (0.95, 1.10)	1.05 (0.94, 1.16)	1.05 (0.84, 1.32)
< 5 years	1,834	0.99 (0.85, 1.17)	1.04 (0.84, 1.30)	0.54 (0.28, 1.03)
5 – ≤ 19 years	1,774	1.01 (0.84, 1.21)	1.02 (0.79, 1.31)	0.95 (0.53, 1.68)
20 – ≤ 64 years	5,160	1.02 (0.92, 1.11)	1.00 (0.87, 1.15)	1.20 (0.91, 1.59)
≥ 65 years	816	0.95 (0.75, 1.21)	1.13 (0.82, 1.55)	1.31 (0.71, 2.42)

^aModel estimates are adjusted for daily average temperature and time trends.

Figure Legends

Figure 1. Three exposure classifications regions and towns grouped in each region with indication of CSO facilities.

Figure 2. Time series of rate of daily ER visits for GI illness [per 1000,000 population, indicted with dots (.)] for each exposure region with of days with extreme precipitation (≥ 99 th percentile) indicated with triangles (\blacktriangle).

Figure 1.

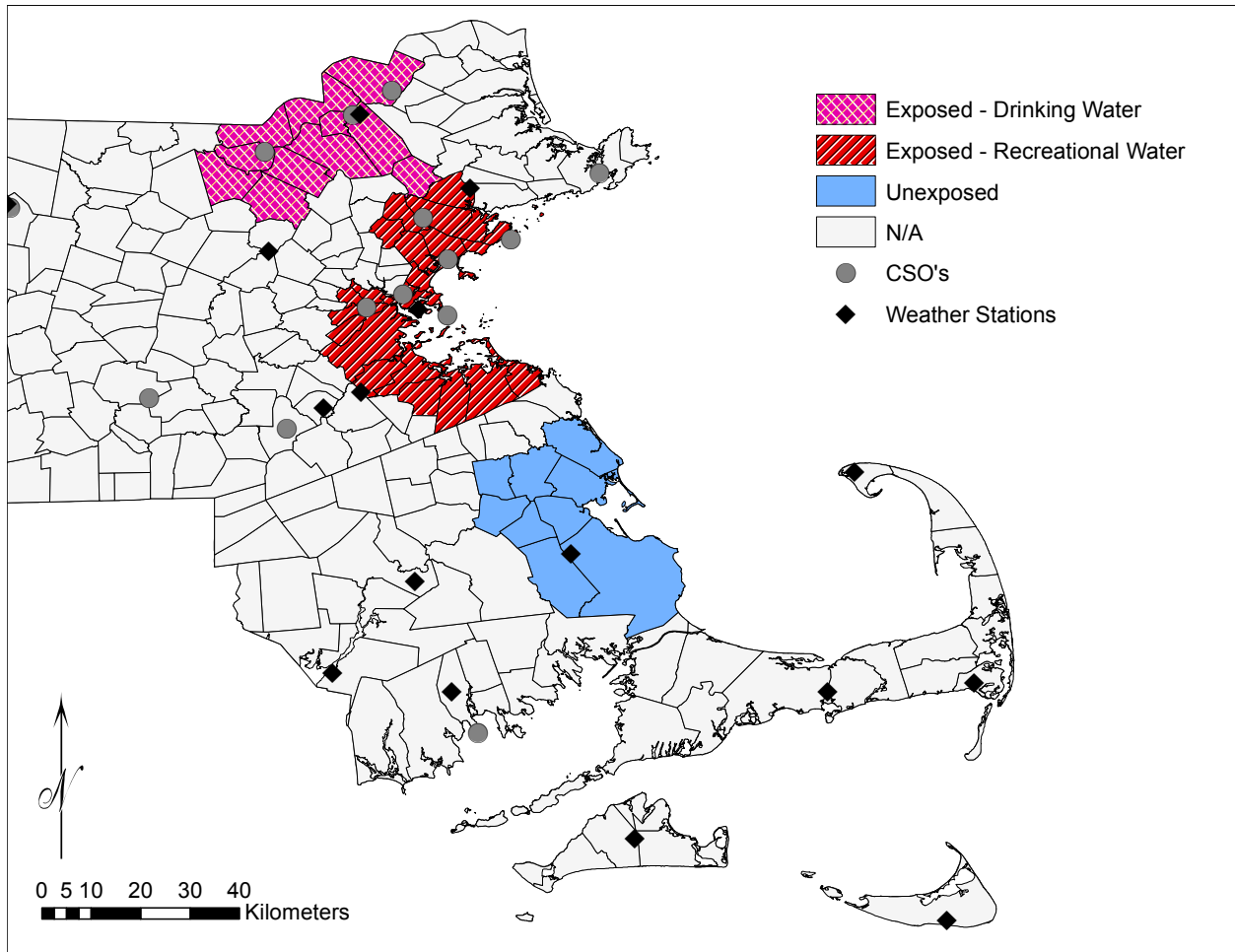


Figure 2.

